AEGIS: Apparatus to Explore the Gravitational Interaction of antiatomS: the R& D programme

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Introduction

The principal reason for constructing the Antiproton Decelerator (AD) at CERN has been the prospect for precision measurements with antihydrogen atoms. Two experiments (ATHENA and ATRAP) were approved in 1997, both proposing a three-step programme: 1) production of cold antihydrogen atoms, 2) trapping and cooling of antihydrogen; 3) comparison of antihydrogen and hydrogen atoms, with very high precision.

Step #3 contains the physics that makes these experiments relevant to CERN's research: program: a) high precision tests of CPT invariance, to a level of 10^-15 or better, and b) the first precision measurement of the gravitational acceleration of antimatter.

The goals of step #1 have been achieved in 2002, when the ATHENA and the ATRAP collaborations demonstrated [1] the production of large amounts of cold (sub-eV) antihydrogen atoms. The experiments used similar methods for antiproton capture and recombination of antiprotons with positrons, but different schemes for positron accumulation and antihydrogen detection. ATHENA has measured the absolute antihydrogen production rate into all n-levels and its temperature dependence. ATRAP measured the velocity of highly excited antihydrogen atoms in a narrow n-range (n ~40-50) that travel parallel to the magnetic field axis.

We believe that progress towards precision physics now requires focusing on the goals of step #2 – trapping and cooling of antihydrogen. While the main experimental challenges have been known for many years, little progress has been made towards their solution since the AD came into operation. The NEAT collaboration is therefore actively pursuing an R+D program that will focus on problems that have to be resolved before a credible proposal for antihydrogen precision measurements can be submitted to the SPSC. Fortunately, many of these developments can be done using protons, electrons, and hydrogen atoms, thus permitting experiments in a laboratory environment, also during the PS shutdown period in 2005. In particular, we will concentrate on:

1) the experimental study of electric and magnetic field configurations (magnetic multipole traps) allowing the production and storage of antihydrogen in the same volume;
2) the development of a Lyman-Alpha laser with sufficient strength for the laser-cooling of antihydrogen atoms;
3) the experimental study of producing positive antihydrogen ions.

The motivation behind this program of R&D is a strong interest in testing the gravitational interaction of antimatter, and the conviction that physically relevant experiments on antihydrogen are now hampered by the lack of available technology. We are submitting this Letter-of-Intent to the SPSC to describe this ongoing R&D program and to express our interest in proposing a new experiment for antihydrogen precision measurements once the necessary technical solutions have been found. Given the time scale of preparation, construction, and measurements, we believe that the earliest time for antiproton experiments based on the results of this R&D will be in 2007. The Italian part of the collaboration has submitted a funding proposal to INFN, which is currently under review.

Physics goals

Tests of the validity of the Weak Equivalence Principle (WEP) for antimatter (antihydrogen) represent the long-term scientific interest of our group. Gravitational measurements can be performed either by direct methods - through the measurement of the gravitational acceleration of hydrogen and antihydrogen atoms in the Earth's gravitational field – or through high precision spectroscopy of antihydrogen and comparison with hydrogen. These spectroscopic measurements should also allow a sensitive test of CPT invariance.

In the gravitational sector, no direct measurements exist about the gravitational force on antimatter. Therefore even a measurement performed with relatively low precision (around 0.1%) will represent an important milestone. The indirect limits that can be obtained on the validity of the WEP for antimatter using data provided by experiments on matter, together with general physics principles, set the scale for the ultimate experimental precision that has to be reached (here, we are not referring to any particular theoretical model leaving room for possible differences in the gravitational force for matter and antimatter). Arguments related to the effect of virtual electron-positron pairs in atoms with different Z values together with the actual experimental limits on the independence of the gravitational force on the body compositions, exclude any difference in the gravitational acceleration g of matter and antimatter larger than about 10^{-6}-10^{-7} [2]. Several critiques of this argument have been discussed in the literature, emphasizing the need of a direct measurement [3,4,5,6].

Additional limits on the validity of the WEP for antimatter systems are obtained using the neutral Kaon system data, assuming the validity of CPT and remembering that, as a consequence of General Relativity, every clock shifts its frequency in a gravitational field. Then if ω is a clock frequency in absence of gravitational interaction, then the corresponding clock frequency when the gravitational potential is U is given by $\omega' = \omega\left(1+\frac{U}{c^2}\right)$. If an antimatter system violates the WEP, then we could write $\omega' = \omega\left(1+\alpha\frac{U}{c^2}\right)$. α is a parameter describing WEP violation. By using the neutral Kaon mass measurements and defining $\omega = m(K^0)/c^2$ and $\overline{\omega} = m(\overline{K^0})/c^2$, a limit on a WEP violation in the Kaon system of 2.5 10^{-18} has been obtained [7], assuming that the inverse square law holds up to super-galactic distance scales and using $U/c^2 = 3\ 10^{-5}$. Adding information from the quark model, a limit $\alpha < 2 10^{-8}$ is obtained for the proton-antiproton system [7].

Competitive limits about the validity of the WEP for the Hydrogen-Antihydrogen system could be obtained through the high precision comparison of the frequencies of the 1S-2S transitions for these two systems and accepting all the hypotheses leading to the above-mentioned limit concerning the neutral Kaon system. A precision of 10^{-15} in the hydrogen and antihydrogen 1S-2S transition can be interpreted as a WEP test with 10^{-11} sensitivity.

A precise measurement of the 1S-2S transition frequency for hydrogen and antihydrogen in two regions where the gravitational potential changes by an amount ΔU provides a test of the validity of the weak equivalence principle for antimatter free from assumptions about the validity of CPT (null red shift experiment). For any clock the validity of WEP means that $\frac{\Delta\omega}{\omega} = \frac{\Delta U}{c^2}$, where $\Delta\omega$ is the difference of the clock frequency in two space-time points where the gravitational potential changes by ΔU. The eccentricity of the Earth's orbit around the Sun produces a change of the Solar potential $\frac{\Delta U}{c^2} = 3\,10^{-10}$ during a three-month period. By measuring the 1S-2S transition of hydrogen and antihydrogen with 10^{-15} precision, a WEP test with a precision of the order of 10^{-6} could be performed.

Direct measurements of the gravitational acceleration of cold atoms in the Earth's gravitational field using atom interferometry methods have been shown to be able to achieve a sensitivity of 10^{-9} [8], with higher sensitivities expected to be within reach soon. Once a sample of very cold (sub meV) antiatoms is available, the same precision can be obtained on the gravitational interaction of antimatter [Appendix I].

For CPT, the best direct limits in the lepton sector are $\sim 10^{-12}$ for the electron-positron magnetic moment (g-2) [9] and, in the baryon sector, $\sim 10^{-10}$ for the antiproton-proton charge-to-mass ratio [10]. A more precise indirect limit of $\sim 10^{-18}$, although not completely assumption free, is obtained using neutral kaon data [11]. The comparison of the 1S-2S transition for hydrogen and antihydrogen atoms to a precision well below 10^{-12} will be a competitive CPT test in the baryon-lepton sector, although reaching such a precision requires not only trapping, but also cooling, of antihydrogen atoms [Appendix II].

Current status and conceptual design

The accumulation and cooling of antiprotons and positrons in two separate regions of the apparatus has been demonstrated by the ATHENA collaboration [12]. These techniques, which yield high numbers and densities of available particles and a high antihydrogen production rate, will very likely be maintained in the concept of the future experiment. This ideal apparatus would consist of an antiproton catching and cooling region, a positron accumulation region, a mixing region and a possibly separate measurement region.

Antiprotons have been captured and cooled by electrons in a Penning-Malmberg type trap, with typical numbers of 10^4 antiprotons per AD shot, trapped and cooled to the ambient cryogenic trap temperature in a time scale of 30-40 s, using electron plasmas consisting of several 10^8 electrons with a density of the order of 10^8 / cm^3. Work in progress has indicated the possibility of radially compressing the antiprotons cloud to less than a millimeter.

The positron accumulation scheme developed by C. Surko's group at San Diego, and used by the ATHENA collaboration has shown itself to be very efficient. The technology is well tested and the complete apparatus is commercially available from the company First Point Scientific. The ATHENA positron accumulator typically achieves accumulation rates of 10^8 e^+ / 200 s, transfer efficiencies (from the positron accumulator into the recombination region) of better than 50%, plasma radii of less than 1mm and plasma densities of more than 10^9 / cm^3; the parameters of the positron plasma are monitored non-destructively [13], and can be modified by means of the so-called 'rotating wall' method [14].

With the parameters of the present ATHENA experiment, antihydrogen production rates of several hundred Hz have been reached [15]. In this set-up, antiprotons injected into the positron cloud with energies of a few tens of eV interact with the positrons until a low relative velocity is reached. Antihydrogen production starts after this cooling process has taken place (a few tens of ms) [16]. The energy of the antihydrogen atoms is of course determined by the energy of the antiprotons; however, the dynamical factors influencing this energy (the interplay between cooling and recombination in the plasma, the effect of the positron plasma rotation) are still under investigation.

The characteristics of the produced antihydrogen atoms have not yet been completely determined. Their spatial distribution is consistent with isotropic emission from the axis of the positron plasma. Their velocity distribution in an ATHENA-type setup is currently unknown, although if thermal equilibrium between antiprotons and positrons occurs before formation of antihydrogen, then a significant fraction of the produced antihydrogen atoms should have a temperature comparable to that of the positrons. A simulation [17] of the recombination process of the ATHENA and ATRAP experiments indicates that for an ATHENA-type setup, a significant fraction of antihydrogen atoms formed in a large, high-density e^+ plasma may be strongly bound, and a significant fraction have a velocity of the order of 100 m/s for a positron plasma temperature of 4 K. This analysis also underlines the great importance of using an extended, high-density positron plasma, and, to a lesser degree, working at as low a temperature as possible.

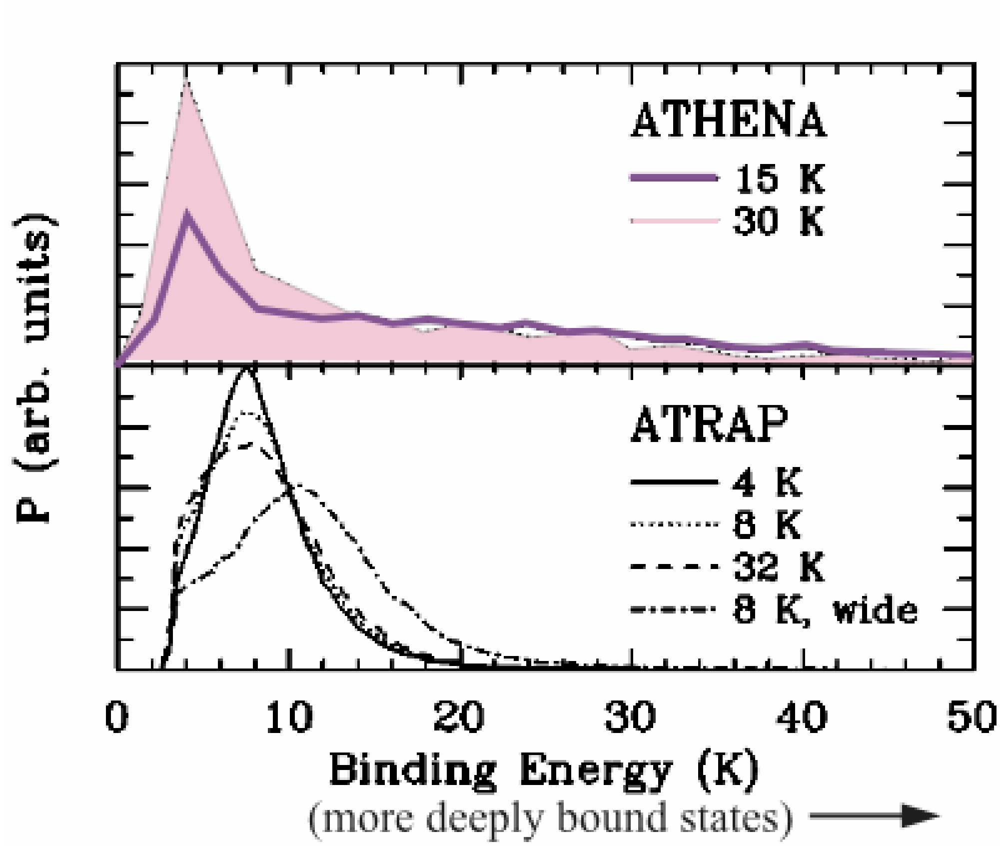

Fig. 1: Binding energy of antihydrogen atoms as determined in [17]. More deeply bound states are to the right. The enhanced presence of more deeply bound states in the ATHENA experiment with respect to the ATRAP experiment is argued to be due to stronger collisional de-excitation in the much more extended and denser positron plasma in the former.

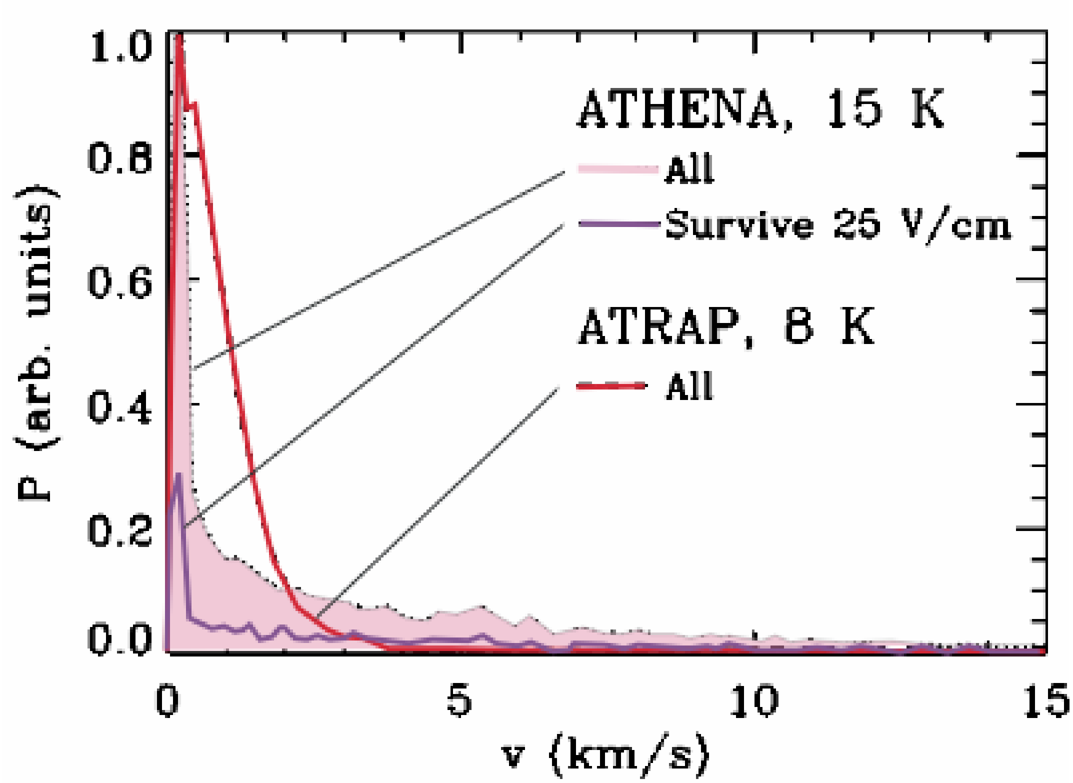

Fig. 2: Velocity distribution of antihydrogen atoms from [17]. Antihydrogen atoms with a velocity of less than 0.1 km/s would be trappable in the proposed multipolar neutral trap.

Any physically relevant studies of these antihydrogen atoms however requires trapping and cooling them to mK temperatures, since the achievable resolution on spectroscopy of uncooled atoms would not allow to obtain a better bound on CPT than what is presently available, and would not allow a high precision measurement of the gravitational interaction of antimatter.

Technological challenges in trapping antihydrogen

We are pursuing two independent paths towards trapping and cooling of antihydrogen. In the first set of experiments, we wish to attempt to study a configuration in which neutral antihydrogen atoms can be produced and trapped, while in the second set of experiments, we will study the feasibility of laser-stimulated antihydrogen ion production. Neither of these experiments requires antiprotons for the methods to be validated.

1) Multipole trap for simultaneous confinement of neutral and charged particles

The presence of the magnetic field gradient needed for the neutral trap strongly influences the stability of the confinement of the charged particles. One of the major issues is the breaking of the rotational symmetry of the charged particle traps induced by the presence of the radial magnetic field having values comparable with the axial magnetic field of the charged particle trap.

The conceptual design that we are currently investigating foresees a mixing region that allows the confinement of positrons, antiprotons and the neutral antihydrogen atoms in the same volume. This is achieved by superimposing a nested trap for the charged particle confinement with a trap for antihydrogen, made by a radial multi-polar magnetic gradient together with an axial magnetic bottle. The details of the magnetic trap are under investigation.

The radial magnetic field will be $B_r = B_{r0}\left(\frac{r}{r_w}\right)^n$ where n=1 in case of a quadrupolar radial field as in the Joffe- Pritchard case, n=2 for a sextupole field and so on. r_w is the nested trap radius. The axial magnetic field will include the uniform magnetic field needed for the charged particles and the axial gradient needed for antihydrogen confinement. Neutral (anti)hydrogen atoms can be confined in such a configuration if they are produced with an energy lower than the trap depth (of the order of 0.5 K), and if their magnetic moment is anti-parallel to the magnetic field direction ("low field seeker"). Assuming that all atoms are in the ground state, and that their temperature is only due to the positron temperature, one would expect several trapped antihydrogen atoms in a 0.5 K well per mixing cycle in a 4.2 K apparatus recombining (as in ATHENA) 20% of the typical 10^4 antiprotons available.

The neutral trap magnetic field gradient can be realized either by permanent magnets or by super/normal-conducting coils. Permanent magnets offer the possibility to design an apparatus where a cryogenic vacuum chamber is in communication with a room temperature vacuum chamber, while maintaining the conditions for the radial confinement of cold antihydrogen atoms, which would allow transport of cold antihydrogen from the production region to a measurement region suitable for a high precision laser experiment. On the other hand, variable-current conducting coils permit adiabatic cooling procedures that in principle would allow reaching very low energy values (see later).

2) Laser-induced antihydrogen ion production

If antihydrogen ions (the antimatter partner of the H- ion) could be produced, it would be relatively straightforward [18] to cool these ions sympathetically (e.g. using trapped Be+ ions), and then strip off their positron by a short laser-pulse.

We are presently designing a second test experiment that would study the matter-equivalent of this process, by studying laser-induced recombination of hydrogen atoms and electrons. We will use a set-up inside a 3 T superconducting magnet, allowing to trap and to store dense clouds of electrons, and to control the partial pressure of atomic hydrogen. We will study if the production of H^- ions can be stimulated by an infrared laser (1641 nm) tuned to the transition frequency between the continuum and the bound state (E = -0.755 eV). The inverse process, H^- photodetachment, has a cross-section of about $10^{\wedge-17}$ cm^2 in the relevant energy range [19]. Theoretical work is in progress to calculate the recombination cross-sections under realistic conditions.

Validation experiments and milestones

The two sets of experiments, which will run in parallel, explore two different possible paths to trapping antihydrogen. The milestones involved in the two are different, but successfully validating either technique would allow designing and proposing an experiment to study trapped antihydrogen.

1) Neutral trap milestones

In a prototype experiment (that does not, in a first step, include an axial magnetic bottle, but only a radial multi-polar magnetic gradient) using permanent magnets (already ordered from the company Vacuumschmelze), we will investigate the stability of electron and proton clouds under conditions very similar to those currently in use in the ATHENA experiment to produce antihydrogen. The dimensions of the permanent magnet were chosen to allow it to fit inside an existing 3T superconducting solenoid which also houses a multi-ring electrode system providing the nested trap for (anti)proton and electron (positron) trapping; the set-up is in an advanced state of installation. The radial multi-pole magnetic field generated by the permanent magnets covers the region of the central electrodes, and produces a gradient that will confine neutral atoms in the radial direction. The depth of this well corresponds to antihydrogen temperatures of few hundred millikelvin. The apparatus can be operated both at room temperature, as well as inside a helium cryostat. Diagnostics based on non-destructive detection of the plasma modes, together with high-sensitivity destructive detection (micro-channel plate and imaging on phosphor screen) have been installed. Ultrahigh vacuum is ensured also at room temperature by a proper choice of the materials and by coating all free surfaces of the apparatus with a NEG getter developed by the CERN vacuum group.

Achieving plasma stabilities of the order of 10s of seconds with such a setup is an essential requirement for us, and constitutes a first milestone.

The second milestone is the observation of electron cooling of protons. It has been shown in ATHENA that this process leads to the formation of antihydrogen and can thus be used as a proxy signal for the formation of hydrogen atoms.

2) Laser-stimulated production of antihydrogen ions

While the production of hydrogen ions via laser-stimulated photo-attachment of an electron to a proton may be difficult experimentally, its observation is relatively straightforward. The spontaneous transition rate of a mix of H and e^- into the only bound state of H^- (binding energy of 0.755 eV) can be estimated [19], but is low compared to that of spontaneous radiative transitions since the dipole moment of the H atom is small; this rate can be enhanced by use of a 1641 nm laser. Observation of even small numbers of H^- in a dump of the trapped charged particles would constitute the essential milestone for this technique.

The experimental results, and in particular the dependence of the recombination rate on electron and hydrogen densities, will give valuable information if a similar scheme would be applicable to antihydrogen when formed inside a long, dense positron cloud.

Summary

We would consider achieving the milestones of either method (observation of cooling of protons by electrons in a multipolar magnetic trap or detection of H^- ions) as sufficient grounds to propose an experiment using antiprotons whose first goal would be to demonstrate trapping of antihydrogen atoms. This could lead towards a possible measurement of the gravitational interaction of antihydrogen based on interferometric techniques.

To proceed towards achieving the above milestones, a series of experiments with protons, electrons and ions are currently under way, and a positive resolution of these challenges is a prerequisite for any experiment wishing to study antihydrogen atoms. We emphasize that these experiments can and will be carried out without requiring antiprotons. In parallel, we are also working towards the subsequent step, that of cooling trapped antihydrogen atoms [Appendix III].

A detailed description of the experimental setup needed to reach the physically interesting regime of trapped antihydrogen atoms at a temperature of 1 mK or less is beyond the goal of this report. Once these milestones have been reached, and the necessary technologies are available, an AD experiment incorporating these technologies will be proposed. Given the necessarily complex nature of these technologies, we do not foresee that we will be in a position to attempt to trap antihydrogen atoms before 2007.

Appendix I: Direct gravity measurements

Laser cooling of antihydrogen is essential to obtaining very cold antihydrogen atoms on which direct gravitational effects can be observed with high precision. Assuming antihydrogen atoms with mK energy are available, then direct gravity measurements can be performed by studying the time of flight distribution of atoms launched vertically from a trap. The radial motion can be limited by an (axially invariant) radial magnetic multipole. Because the initial velocity cannot be measured, the information about g has to be extracted from the study of the shape of the time-of-flight distribution. The arrival time is obtained by the annihilation signal and the detection efficiency is close to one. For a given flight height L there is a cutoff time $t_c = \sqrt{\frac{2L}{g}}$ beyond which no atom will be detected. The shape of the time of flight distribution around the cutoff time can be fitted to determine the gravitational acceleration g. For a 50 cm long drift tube, the cutoff time is 319.4 ms. As a reference, about 10^4-10^5 antiatoms coming from a Maxwell type distribution having few mk as mean energy have to be launched to obtain sufficiently high statistics in the time of flight distribution around the cutoff time. Measurements of this type could allow accuracies of the order of 10^{-3} to be achieved.

Atom interferometry is experimentally accessible by employing either slits and diffraction gratings (made by material structures or periodical light fields) to split and recombine beams of atoms or by splitting the beam with a electromagnetic field which induces momentum recoil and transitions between two internal states [20]. Both of these techniques have been demonstrated to exhibit high sensitivity to the gravitational acceleration in experiments with cold atoms. It has been shown that an atom interferometer may be used to measure g with a precision of 1 part in 10^{10} [20], and a precision of 3 parts in 10^9 has been experimentally reached [8]. In this experiment, cold cesium atoms are vertically launched from a magneto-optical trap and a proper sequence of light pulses separated by a time interval T is applied to them. The absorption of the photons with wave number k_{eff} by the atoms induces transitions between two internal states and atom recoil. At the end of the pulse sequence, the number of atoms in one of the internal states versus the phase of the last light pulses shows a typical sinusoidal interference pattern with a phase shift $\Delta\phi$ due to gravity $\Delta\phi = k_{eff} g T^2$. The high precision reached in this experiment is mostly due to the very low energy of the atoms (μK regime).
Some of us are already working on an experimental apparatus (MAGIA) using these technologies and aiming to measure the gravitational constant G with Rb atoms [22].

Simulations and R&D are in progress with the aim to evaluate the performances of a gravity measurement setup using a Mach-Zehnder matter wave interferometer combined with a silicon detector. These devices are commonly used for measurements of gravitational acceleration of cold atoms and neutrons [23]. To combine such an interferometer to a well-prepared antihydrogen beam was already proposed in 1997 by Phillips [24]. It basically consists of two almost identical phase coherent transmission gratings with roughly 50% grating spaces, placed in equal distances to each other and the detection plane (fig. 3 right). Only the zero's (50% -) and first orders (25% intensity) of diffraction are of importance under these conditions generating an interference pattern on the absorber with the same period as that of the gratings.

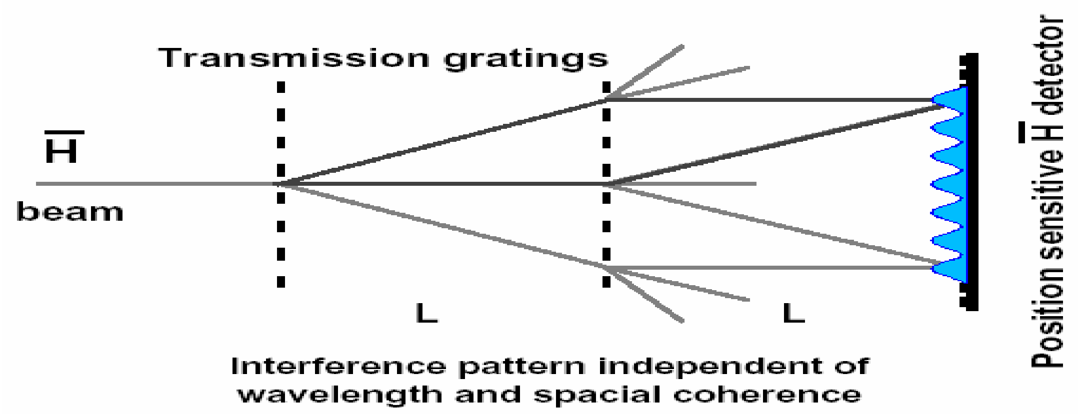

Fig 3. A possible interferometer with two identical transmission gratings and the position-sensitive antihydrogen detector.

A priori such a type of interferometer does not require a coherent atomic source since its interference pattern is independent of source dimension and wavelength of the test atoms, i.e. the atomic source must not necessarily be point like and the atoms can be distributed in energy. However, the divergence of incoming atoms must be sufficiently small not to smear out the interference pattern. In the case of gravitational acceleration along the direction of diffraction, the interference pattern will shift by the same amount that the atoms fall during their transition time. The phase shift $\Delta\phi$ induced by the gravitational force is

$$\Delta\phi = \frac{1/2gt^2}{d} = g\frac{L^2}{dv_x^2}\pi$$

where t is the flight time, L is the distance between the gratings, d is the line spacing and v_x is the velocity in the direction perpendicular to the grating.

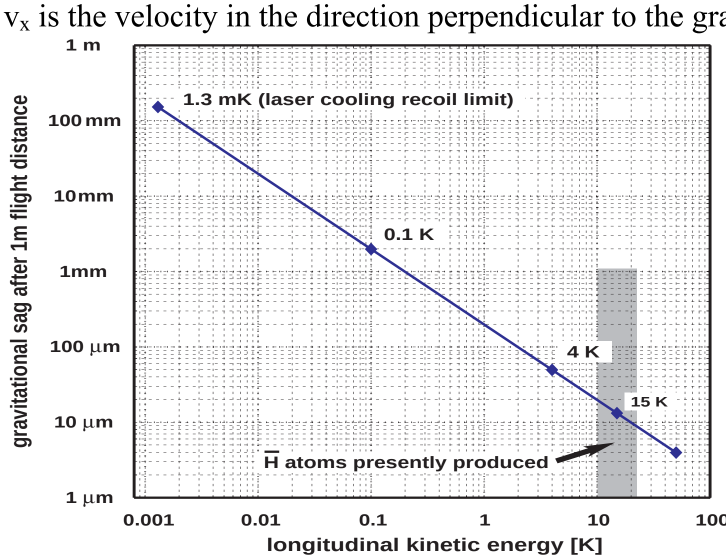

Fig. 4 Gravitational sag of antihydrogen in the Earth's gravitational field after 1m flight distance (assuming g=9.81 m/s^2)

This phase shift can be determined with high precision by comparing to the interference pattern without a shift at vertical slit orientation, i.e. by rotating the setup around the beam axis. The phase of the interference pattern is usually scanned mechanically by means of an additional grating which can be moved with high precision. Here we propose the use of Si micro strip detectors instead of an analyzer grating since it directly delivers spatial and temporal information of antihydrogen atoms impinging on its surface. The main advantage above all is a possible offline combination of interference patterns stemming from atoms of different energy bins. This requires however a time of flight measurement, i.e. the knowledge of the departure time of an atom. Since travel times, for atoms considered here, are in the range of 100ms, only a moderate resolution on this value has to be obtained. The detector is mounted in a fixed position to the gratings, avoiding precise mechanical movement and feedback systems in the vacuum vessel. The latter usually take the form of an optical interferometer attached to the transmission, as well as the analyzer gratings. Using a gadolinium absorber in front of the silicon the setup can be exposed to a thermal neutrons source for functionality tests and calibration. Gadolinium has a very high cross section for thermal neutrons and can be evaporated onto Si-sensor surfaces. After capturing a neutron a nucleus undergoes β–decay under emission of an electron in the 100 keV range which can be detected in the sensor.

Appendix II: 1S-2S Doppler-free two-photon spectroscopy in the trap

The 1S-2S two-photon transition in hydrogen is extremely narrow: its quality factor Q is $Q = \frac{\omega_0}{\gamma_N} \approx 2\,10^{15}$ where the line width is limited by the natural decay lifetime $\gamma_N = 2\pi 1.1 rad/\sec$. The frequency of the 1S-2S transition in hydrogen has been measured with a resolution of 1.4 10^{-14} [25] using a cold hydrogen beam traveling collinearly with a 243 nm standing wave (Doppler free two photon absorption). Only very slow atoms having velocity below 80 m/s (that is with energy lower than 400 mK) gave a contribution to the signal. These atoms are selected from a cold (7 Kelvin) high flux beam. Using hydrogen trapped in a magnetic trap and cooled by evaporation up to 100 μK, a resolution of 10^{12}, mainly limited by the laser stability, has been reached at MIT [26].

Several factors contribute to the shift and broadening of the frequency spectrum. For antihydrogen confined in the magnetic trap, the Zeeman shift is one of the dominant factors.

$$\delta_v = (\alpha^2 \mu_B B)/(8h) \approx 9\,10^4 \; B(Tesla)\,Hz$$

Because an atom with energy E in the trap is confined in the region where $B \approx E/\mu_B$ there will be a broadening of the line of the same order of magnitude.

The transit time broadening due to the fact that the atoms spend a limited time inside the laser beam region is $\delta = \sqrt{\frac{2KT}{m}}\frac{1}{4\pi w_0} \approx 10^5 \frac{\sqrt{T(K)}}{w_0(\mu m)} Hz$ where w_0 is the radius of the laser beam. Assuming w_0=400 micron, T=1- 0.5K, this is lower than the Zeeman effect. Motional averaging effects are not taken into account here.

The typical excitation and detection cycle could be the following :

- after mixing positrons and antiprotons for a proper time (seconds or few tens of seconds) the charged particles are removed and the trap voltages are switched off.
- A 243 nm laser beam is shined along the trap axis for a time T and it is retro reflected creating a standing wave.
- Antihydrogen atoms passing through it undergo Doppler free or Doppler sensitive excitation from the 1S to the 2S state.
- A quenching electric field of about 10 V/cm is applied mixing the 2S state with the 2P state.
- The 2P state rapidly (the lifetime is 1.6 ns) decays towards the 1S state. Atoms with the wrong spin polarization are no longer confined in the trap.
- Unconfined antihydrogen atoms annihilate and are detected with an efficiency close to 100% by an antihydrogen detector surrounding the recombination region (similar to the one used in the ATHENA experiment).
- The cycle is repeated, sweeping the laser frequency to build a spectrum.
- After using most of the atoms the antihydrogen production cycle starts again.

The rate of the Doppler-free two-photon transition is $\Gamma_{1S-2S} = 85 \frac{I^2(W/cm^2)}{\Delta\upsilon(Hz)} Hz$, where $\Delta\upsilon / 4\pi$ is the width of the resonance line and I (W/cm^2) is the laser light intensity in the focus. The ionization of the atoms in the 2S state due to the absorption of the 243 nm photons cannot be ignored. The ionization rate is $\Gamma_{ion} = 9.7 I(W/cm^2) \quad Hz$.

Assuming that the laser pulse duration T is of the order of $\frac{1}{\Gamma_{ion}}$ and using the Zeeman effect as a measure of the line width, then the number of counts N_{count} per laser pulse is expected to be $N_{count} = 7\,10^{-6} N \frac{I(W/cm^2)}{B(T)} \approx 2 10^{-4} N^*$, where N^* is the number of atoms in the trap passing through the laser beam and the values of I=100 W/cm^2 and B=3 Tesla have been used. N* is expected to be very small with respect to the total number of trapped atoms, leading to an expected precision of the order of 10^{10}. This precision on the frequency can be improved upon by a factor of i.e. 100 (by accumulating statistics over 10000 counts), if all the systematic effects are well understood and controlled. The high detection efficiency of the antiatoms has to be compared with the 10^{-6} detection efficiency typical of the trapped hydrogen experiments where the Lyman alpha photons emitted in the 2P-1S transitions are detected.

The count rate and the final precision of the measurement are largely improved if cooling of the antihydrogen atoms can be realized by a suitable Lyman alpha laser source. The final temperature in this case is about 1 mK and the atoms will be confined in a region close to the trap axis where the radial magnetic field value is of the order of 10^{-3} Tesla.

Once the charged particles have been dumped, the axial magnetic field can be reduced to a similar value by lowering the current in the superconducting coils. The Zeeman effect is only 100 Hz in these conditions.
In addition, one has to take into account the possibility that after cooling, the antiatoms can be moved from the production region and captured in a measurement region with low magnetic fields and inside an environment more suitable for high precision spectroscopy. Using 1mk hydrogen atoms, a line width of 1Hz is expected in an atomic fountain experiment [27].

An alternative scheme [28] allowing high precision measurement of the 1S-2S transition involves a "shelving" approach and it do not require a large number of atoms; a powerful Lyman-alpha laser source is needed for this.

Appendix III : Antihydrogen cooling

Trapped antihydrogen atoms will have energies of a several hundreds of mK. This value is still too high for the above-mentioned experiments. Cooling of the confined antiatoms is thus necessary if we want to carry out high-precision experiments with antihydrogen. Laser cooling of antihydrogen by a powerful Lyman-alpha source can provide antiatoms with mK energy. If such a cooling can be performed in the confining trap, then at the end of the cooling process the antiatoms will be localized in a very small region around the trap center. Antiatom manipulation and formation of a beam using a combination of permanent magnets (maintaining the radial confinement) and variable coils providing the axial magnetic field will became conceivable.

We are working on a project to develop a suitable Lyman-α source. Only one cw Lyman-α laser presently exists, at MPQ Munich, albeit with very small output power (20 nW) [29]. The development of a stronger 121 nm laser with high output power has a high priority. Work along these lines is planned at Florence University. A funding request has been submitted to INFN in order to develop a Lyman-α source based on the scheme already implemented by the MPI group, addressing the most critical issues in order to improve the overall efficiency of the system and to generate enough power (μWatt range or higher) to cool the antihydrogen atoms. The proposed scheme consists of using a gas of atomic mercury as nonlinear medium for the process of four-wave mixing. The electronic level structure of this atom presents bound levels with energies close to that of the Lyman-α transition. This allows a strong enhancement in the non-linear conversion process using light resonant or quasi resonant with intermediate bound states. The system that we will implement differs from the one developed by the MPI group in the choice of the intermediate laser sources, configuration for 4-wave mixing, nonlinear materials and processes. The project is to realize a portable source that can be installed in a real antihydrogen production environment.
The availability of the powerful enough Lyman alpha source is essential not only for antihydrogen cooling but also for further antihydrogen manipulations: we mention for instance that the high precision spectroscopy using the shelving method [28] will become accessible and also that the excitation scheme used with Cs atoms (Raman transition

between two hyperfine levels of the fundamental state) to perform the high precision gravity measurement [8] could then be applied to antihydrogen.

Manipulation of trapped antihydrogen atoms in view of producing an atomic beam requires slow extraction of trapped and cooled antihydrogen atoms from the neutral atom trap. This could in principle be achieved by adiabatically lowering one of the axial confinement barriers, but the feasibility of this method has yet to be demonstrated in a test experiment.

Cooling antihydrogen below 1 mK requires the development of new methods. The evaporative cooling used in the hydrogen experiments is not very promising due to the low number and low density of the confined atoms. A possibility is offered by the use of a procedure used also for charged particles stored in Penning traps which work for single particles and it is not based on particle-particle collisions [30]. This procedure of adiabatic cooling is connected with the conservation of the action integral and is valid for a system undergoing a periodical motion where the frequencies are adiabatically changed. Rough estimations suggest that energies close to the μKelvin range could in principle be reached if this procedure is applied to trapped antihydrogen already cooled by the Lyman-alpha laser.
Numerical simulations are in progress to evaluate the final reachable energy in realistic conditions.

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